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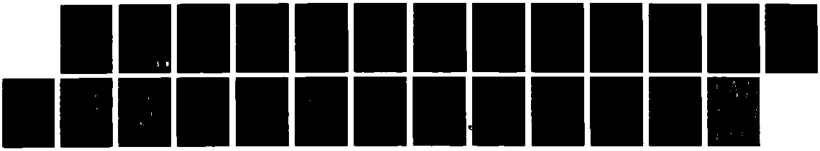

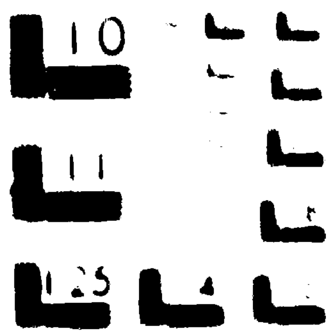
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Measurements of peel force P per unit width are reported for samples of three adhesive tapes, adhering to two different substrates. In all cases, the work of detachment per unit area of bonded interface was found to depend upon the angle θ of detachment, increasing as θ increases. This effect is

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attributed to dissipation of energy in bending the tape away from the substrate at the line of detachment, to a greater degree as θ increases. Extrapolation to $\theta = 0$ is suggested as a simple way of minimizing contributions to the observed work of detachment that arise from bending an imperfectly-elastic adhering layer as it is peeled away from a flat rigid substrate. But at small peel angles the tape tends to stretch appreciably. Peeling at 45° is recommended to minimize both effects.

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1. Introduction

The peel test is commonly used to determine the strength of an adhesive joint (1-6). Scientifically, it has two distinct advantages compared to other test methods: bond failure proceeds at a controlled rate, and the peel force is a direct measure of the work of detachment (7-10). From a practical viewpoint, the peel test is valuable because it is simple to carry out and because it represents a mode of failure under service conditions, e.g., for adhesive tapes. However, variations in the way the test is carried out; in particular, variations in the angle _ at which the adhering layer is detached, have been found to give quite different values for the work of detachment (see refs. 2 and 11, for example, and the results given below).

This anomalous behavior has been attributed to changes in the distribution of tensile stress set up in the interface on peeling at various angles, represented by an angle-dependent stress factor K (11). Alternatively, it has been attributed to a change in the mode of failure, from primarily shear failure at small peel angles to primarily tensile failure at large angles (2). Neither of these explanations seem fully acceptable; the former because within the limitations of stress analysis the factor K can be shown to be necessarily close to unity at all angles of peel (12), and the latter because failure of soft elastic solids under applied shear forces is commonly found to take place by tensile rupture, under the action of the major tensile stress

component (13, 14). Instead, an additional contribution to the work of detachment is thought to arise from energy expended irreversibly in bending the adhering layer away from the substrate, when the layer is imperfectly elastic (12, 15-17). This additional work will be greater at larger peel angles because the layer will be subjected to more severe bending then.

In order to illustrate the possible magnitude of the contribution from bending energy losses to the observed peel force, some experimental results are given here for three commercial adhesive tapes peeled away from rigid substrates at various angles. An extrapolation procedure is then proposed for determining the work of detachment in the absence of bending energy losses. The results are also compared with those obtained by other methods, which correspond to peeling detachment at low peel angles, or with only small bending strains set up in the detaching strip.

2. Theoretical considerations

The peel force $\underline{P}$ per unit width of a detaching strip provides a continuous measure of the work $\underline{G_a}$ expended in detachment per unit of bonded area. The relation between $\underline{P}$ and $\underline{G_a}$ is not generally a simple one, however, It can be derived from energy considerations, as follows.

Consider growth of the debond by a distance $\underline{c}$ (Figure 1). The distance $\underline{d}$ travelled by the force $\underline{P}$ in its own direction is given by

$$d = c(1 + e - \cos\theta) \tag{1}$$

from geometrical considerations, Figure 1, where e is the fractional elongation of the detached strip under the peel force P and θ is the peel angle. Thus, the energy balance becomes (10):

$$P(1 + e - \cos\theta) = (U + G_a) \tag{2}$$

where U denotes the energy expended per unit length in stretching the strip to an elongation e. (Note that it has not been assumed that the deformation process is a linear or an elastic one up to this point.)

We now make the simplifying assumption that the relation between the stretching force P and corresponding extension e is a linear one, with a slope, i.e., tensile stiffness of the adhering layer, of K, so that

$$U = P^2/2K. \tag{3}$$

Equation (2) then becomes:

$$G_a = P(1 - \cos\theta) + (P^2/2K) \tag{4}$$

The second term, denoted ΔG_a hereafter, on the right-hand side of equation 4 is negligibly small when $e \ll 1 - \cos\theta$. In the experiments described below, carried out with **three** commercial adhesive tapes, this condition was satisfied for values of peel angle θ of 45° or greater. Thus, for relatively inextensible tapes or for peel angles greater than about 45°, the work of detachment is given by

$$G_a = P(1 - \cos\theta) \tag{5}$$

to a good approximation. If the work G_a of detachment is a property of the bond and independent of the way in which

detachment is effected, then we would expect the peel force $\underline{P}$ to be inversely proportional to $\underline{(1 - \cos\ )}$. But marked deviations are frequently found from this theoretical dependence. They are the subject of the present study.

3. Experimental details

Three commercial adhesive tapes were used in the experiments; $\underline{A}$, a vinyl-backed electrical tape (3M Scotch brand No. 88), $\underline{B}$, another similar tape (3M Scotch brand No. 35), and $\underline{C}$, a window mounting tape with a stiff plastic backing (3M Catalog No. 2145). Because of the different elastic moduli of the materials used as backings the three tapes had quite different stiffnesses $\underline{K}$ in tension: about 3.5 kN/m for tapes A and B and about 85 kN/m for tape C, per unit width of tape (16). They were applied to two flat rigid substrates; a glass plate and a Teflon plate; and peeled off about 15 min later at various angles in such a way that the line of detachment advanced at a constant rate of 0.17 mm/s.

In order to reduce the amount of bending at the line of detachment some experiments were carried out with tape C as shown schematically in Figure 2, the tape being peeled off around a steel roller having a diameter of 12.7 mm. The tape was backed with a strip of 3M Scotch brand Magic transparent tape, Catalog No. 119, in these experiments, to prevent it adhering to the roller. The additional backing layer was found not to affect the peel strength of tape C, in other experiments. Weights were added to the roller in order to pull the tape into conformity with it at the line of detachment from the substrate. Values of the work of detachment $\underline{G_a}$ were calculated in these cases from the relation:

$$G_a = 2P - W \tag{6}$$

where $\underline{P}$ is the peel force per unit width of tape and $\underline{W}$ is the weight of the roller plus any added weights. In no case was the total force $\underline{P}$ sufficiently large in the experiments with a roller to cause a significant extension of the tape.

All of the experiments were carried out at ambient temperature, about 24°C.

4. Experimental results

Values of the detachment energy $\underline{G_a}$ for tapes B and C adhering to a glass substrate are plotted against the peel angle $\underline{\theta}$ in Figure 3. They are seen to depend strongly upon the peel angle, especially at large angles, rising from about 70 J/m² to about 230 J/m² for tape B and from about 240 J/m² to about 700 J/m² for tape C as the peel angle was increased from small values to 180°. Similar results were obtained with a Teflon substrate, as shown in Figure 4, although the values of $\underline{G_a}$ were much smaller in this case: 40 - 140 J/m² for tape A and 35 - 90 J/m² for tape C.

Results obtained by peeling tape C away from a glass substrate around a rigid roller are shown in Figure 5. When the total weight was increased from the small weight of the roller itself, the detachment energy was found to decrease substantially, tending towards an asymptotic value of about 270 J/m² at large added weights, i.e., when the tape was forced to conform to the gentle curvature of the roller and the degree of bending was minimized. Thus, when the tape was

subjected to only slight bending during detachment, either by employing small peel angles or by peeling around a roller, then the work of detachment was relatively low. When the tape underwent severe bending, then the work of detachment was high.

A quantitative comparison of the values obtained for $\underline{G}_a$ under various test conditions is given in Table 1. In all cases, the work of detachment at 180° was found to be about three times as large as that at low peel angles. When peeling of tape C was carried out at 180° around a roller, however, then the work of detachment was reduced to the same value as at 0°. Thus, the degree of bending imposed on the peeling strip is a major factor in determining the magnitude of the work of detachment, as surmised previously (12, 15-17). It is responsible for large changes in the observed value as the peel angle is increased.

In order to remove the contribution of bending energy losses to the observed peel strength it seems advisable to adopt one of two measures. Either the peel angle should be chosen to be relatively small; say, 45°; or peeling should be carried out using a roller to minimize the curvature of the peeled strip. This latter condition is not easily achieved, however, because the local curvature at the line of detachment is not necessarily equal to that of the roller unless the tape is forced to conform. And when large forces are applied to the tape, additional work $\underline{G}_a$ may be expended in stretching it, equation 4, and must be taken into account.

Similarly, at small peel angles the peel force is much greater, equation 5, and additional work G_a must again be allowed for. A suitable compromise, therefore, is to employ a reasonably small angle of peel, 45°, and to monitor the extension of the peeled strip to ensure that it does not exceed 10-15 per cent. Under these circumstances, the work G_a due to stretching is less than 20 per cent of the total work of detachment. Also, work expended in bending the strip appears to be generally small, as shown in Figures 3 and 4. Thus, the measured work is almost entirely due to simple detachment and can be compared directly with values obtained using other test methods which do not involve significant bending or stretching deformations of the detached material (16, 17). Good agreement is obtained in this way, Table 1.

5. Conclusions

In order to determine the work of detachment with only minor contributions from bending energy losses in the detaching layer, or in its backing, the peel angle should be small. But the peeling strip will tend to stretch significantly when the angle approaches 0°. A satisfactory compromise is to employ a peel angle of 45°, and to monitor the tensile strain set up in the peeling strip to ensure that it does not exceed 10 - 15 per cent.

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Table 1: Values of the work G_a of detachment under different test conditions.

	$G_a(\theta=0°)$[a] (J/m²)	$G_a(\theta=90°)$ (J/m²)	$G_a(\theta=180°)$ (J/m²)	$G_a(\theta=180°)$ using a roller (J/m²)	G_a (small θ) (16, 17) (J/m²)
Tape A on glass	50	80	150	---	34
Tape B on glass	70	110	230	---	---
Tape C on glass	240	270	700	270	215
Tape A on Teflon	43	74	138	---	36
Tape B on Teflon	18	47	98	---	17
Tape C on Teflon	37	48	86	---	34

[a] obtained by extrapolation

Figure Captions

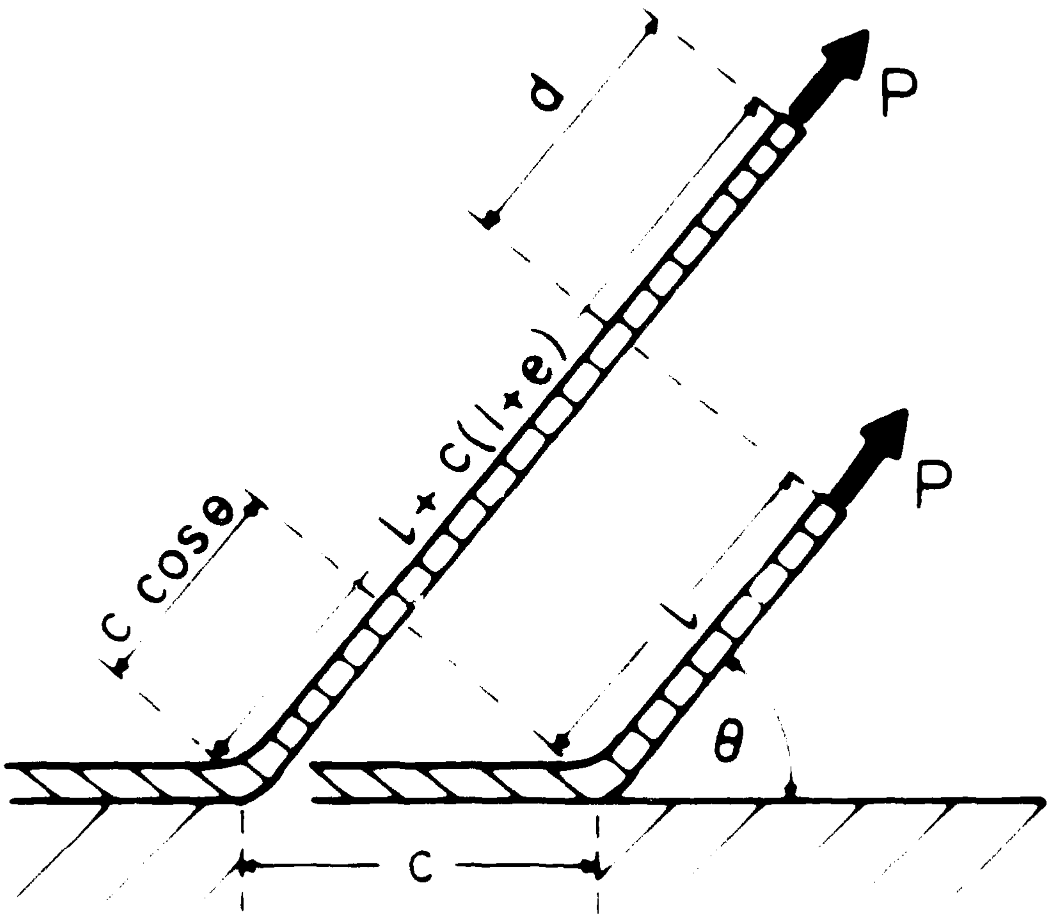
Figure 1: Mechanics of peeling

Figure 2: Peeling around a weighted roller. $\underline{P}$ is the peel force and $\underline{W}$ is the weight of the roller plus added weights, per unit width of tape

Figure 3: Work $\underline{G_a}$ of detachment vs peel angle for tapes B and C adhering to glass

Figure 4: Work $\underline{G_a}$ of detachment vs peel angle for tapes A and C adhering to Teflon

FIgure 5: Work $\underline{G_a}$ of detachment of tape C from glass, peeled off around a weighted roller of total weight $\underline{W}$ per unit width of tape



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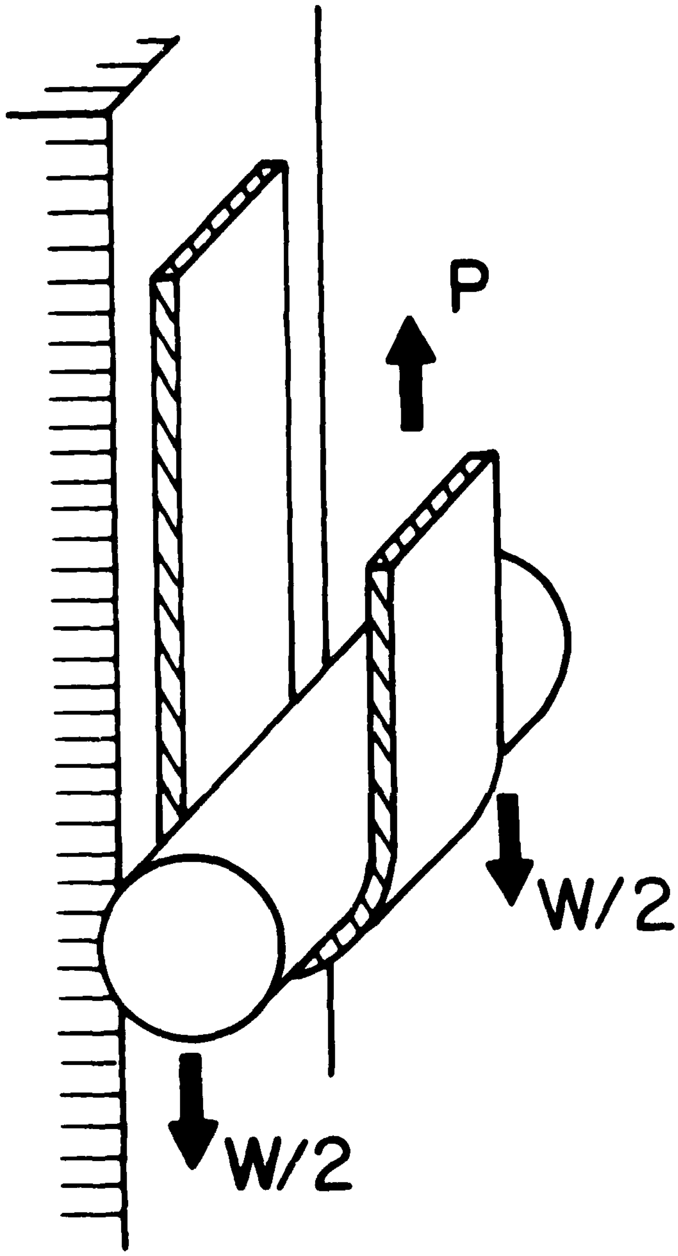
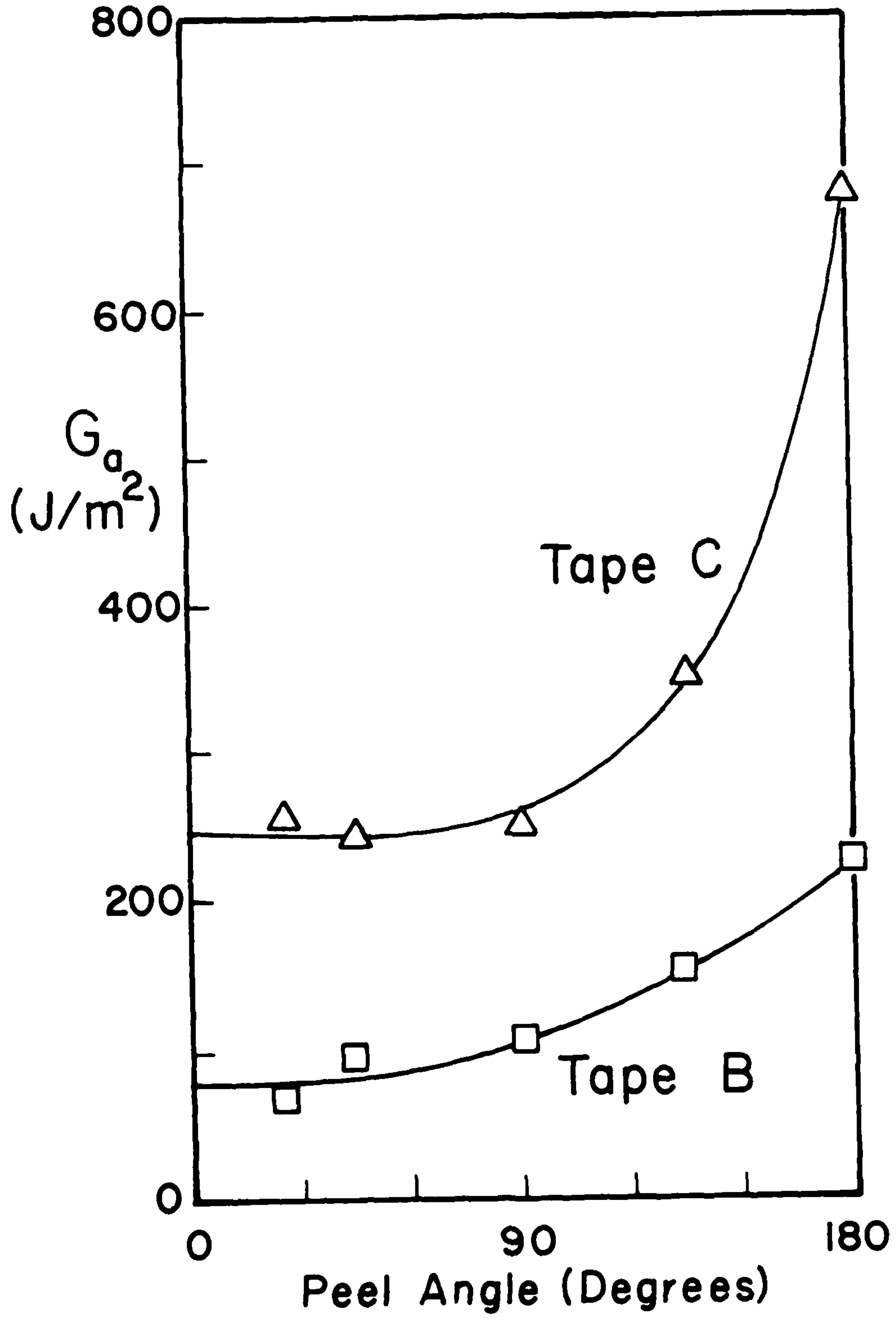
P
c cosθ
L
θ
c


P
W/2
W/2


800
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400
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G_{a_2}
(J/m^2)
Tape C
Tape B
0
90
180
Peel Angle (Degrees)

Figure 3.

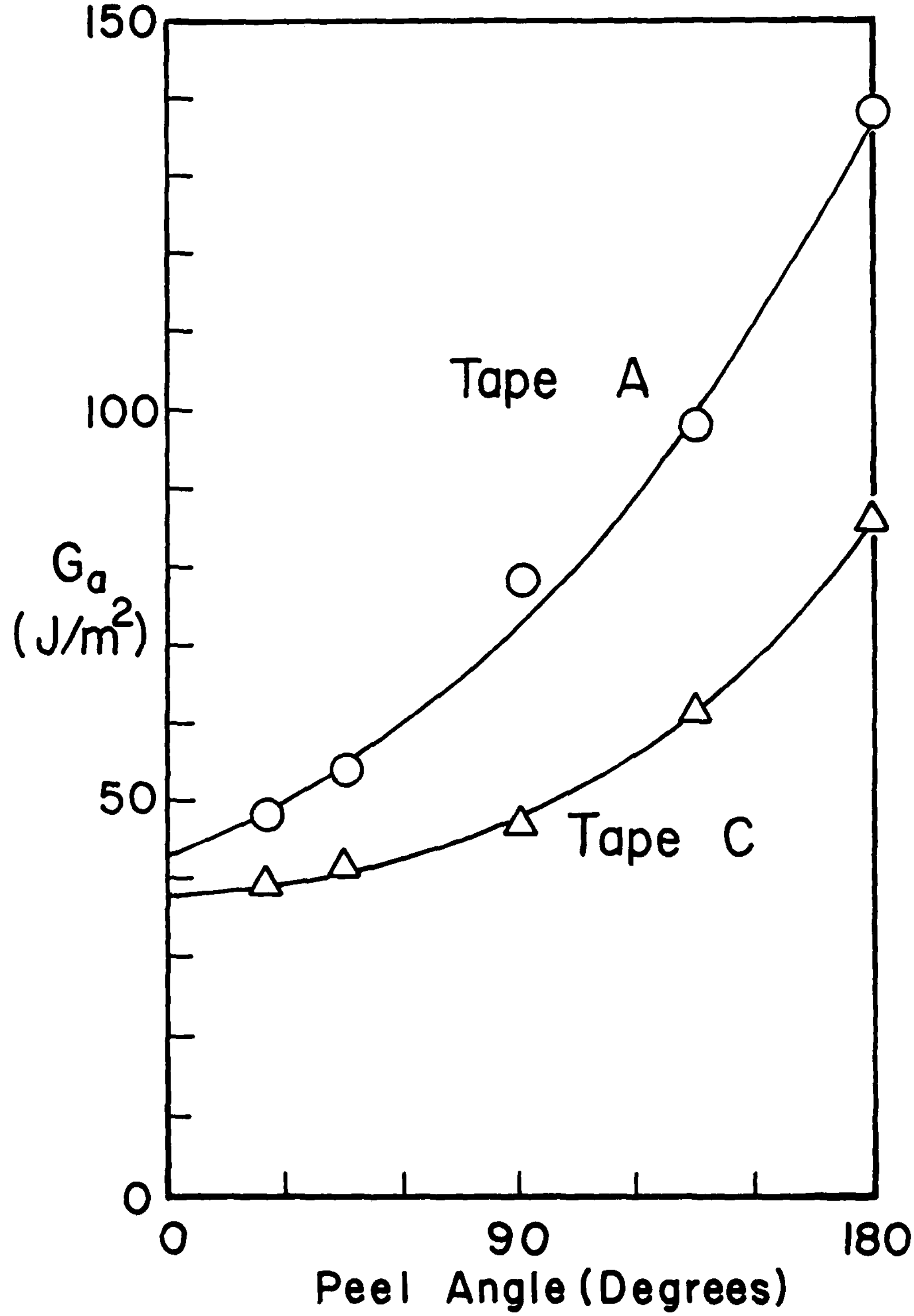
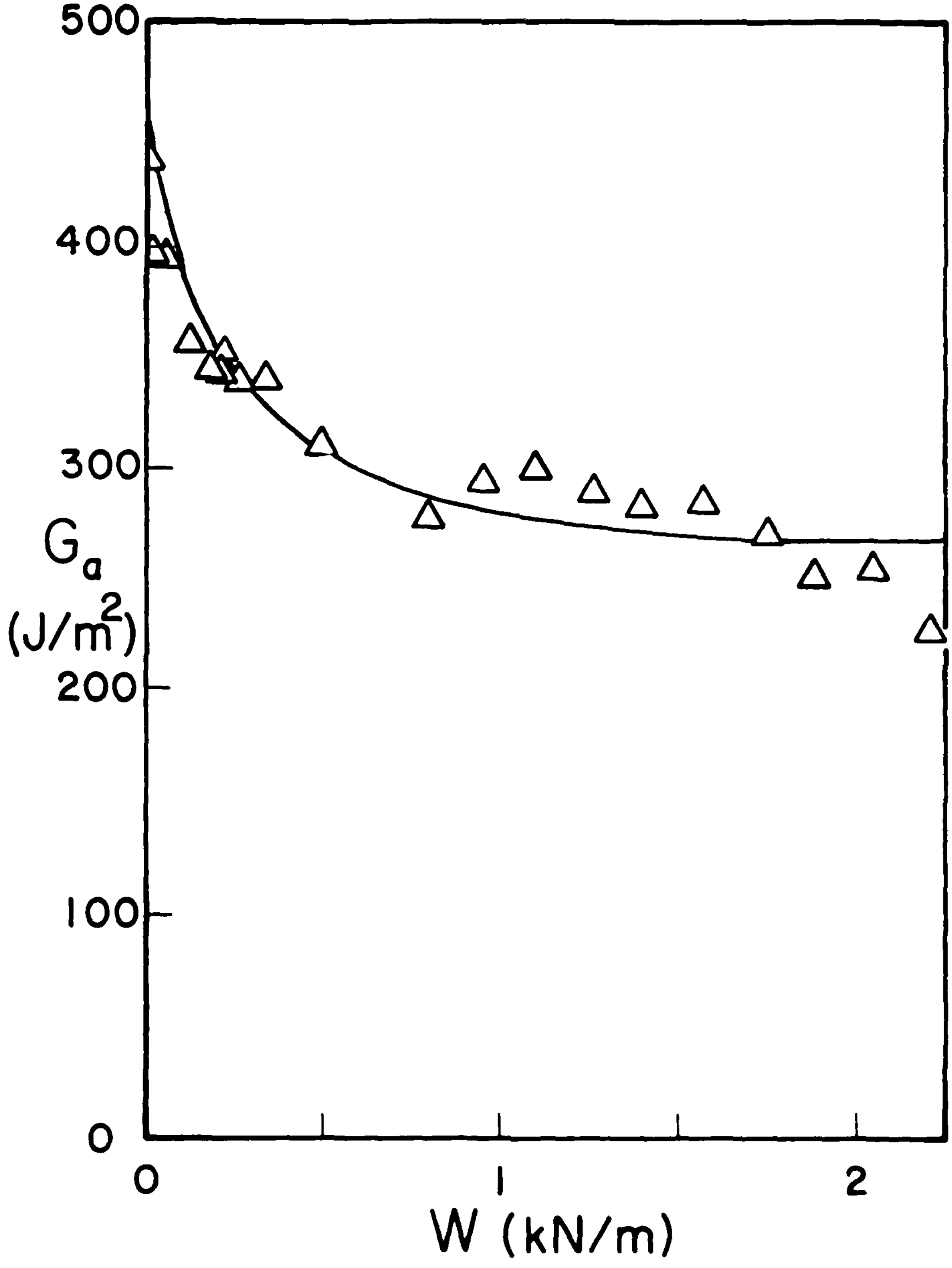


Figure 4.



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